
LES Investigation of Wake Development in a Transonic Fan Stage for Aeroacoustic Analysis

Chunill Hah

Chunill.Hah-1@nasa.gov

NASA Glenn Research Center

Cleveland, Ohio

United States

Michael Romeo

Kent State University

Department of Computer Science

Kent, Ohio

United States

ABSTRACT

The development of the fan wake in a transonic fan stage (NASA R4 fan stage) was investigated in detail with the Unsteady Reynolds-averaged Navier-Stokes (URANS) approach and a Large Eddy Simulation (LES). The primary focus is to compare simulation results from the two approaches with the available experimental data so that some guidance can be developed for future applications to aeroacoustic studies of the fan flow field. Many previous studies on fan noise have indicated that the generation of noise in the fan stage changes with the fan RPM, fan tip clearance, fan loading, and the configuration of the fan stage geometry. Also, it has been reported that the development of the fan wake is significantly different among different designs under similar operating conditions. Therefore, an accurate measurement and/or numerical simulation of the fan stage flow field are required to understand the generation of noise in a particular fan stage. For numerical simulation, URANS has been applied for many previous studies. Although some studies of fan noise generation based on URANS flow simulations have shown promising results, higher fidelity CFD tools, such as LES, are pursued for a reliable physics-based assessment of fan noise generation. The present study indicates that the major difference in the simulated flow fields from URANS and LES is how the small eddies are calculated in the fan stage. When the small eddies play an important role in the generation of fan noise, a higher-fidelity CFD tool, like LES, gives a much more accurate and realistic flow field for noise generation assessment.

Keywords: Transonic Fan Stage; Wake Decay; LES

NOMENCLATURE

AST	Advanced Subsonic Technology
DNS	Direct Numerical Simulation
LDV	Laser Doppler Velocimetry
LES	Large Eddy Simulation
PSD	Power Spectral Density
URANS	Unsteady Reynolds-averaged Navier-Stokes

1.0 INTRODUCTION

In the mid-1990s, NASA conducted an Aircraft Noise Reduction Program through the Advanced Subsonic Technology (AST) program. One of the two main efforts were focused on reducing engine noise. Envia [1] gave a comprehensive review of the program. A major source of noise in aircraft engines is from the fan when operating near airports at takeoff and approach conditions. Therefore, many experimental and numerical studies have been conducted to develop and validate many concepts for fan noise reduction. In parallel, many experimental tests were conducted to identify and characterize noise sources within a fan stage of the turbofan model. The simulated flow field in this study is from one of the last experimental tests of the AST program.

The wake from a fan rotor is highly three-dimensional. The complex three-dimensional structure of a fan wake is shaped by the spanwise variation of the blade loading, unsteady vortex shedding, local boundary layer separation, and spanwise mixing downstream of the fan's trailing edge. Large amount of computational investigation of the fan wake development have been reported. The majority of previously reported computations of fan wake development/decay are based on RANS and URANS approaches. The computational results of fan wake development from URANS depend heavily on the applied turbulence closure modeling. It is generally believed that the underlying flow physics of three-dimensional fan wake decay is not yet fully understood. To obtain more realistic flow simulations, higher fidelity analysis tools based on a direct numerical simulation (DNS) and LES are being applied for turbomachinery flow analysis [2, 3, 4, 5, 6].

In the current study, both URANS and LES are applied for the study of the wake development in the NASA R4 fan stage. The primary objective of the current study is to compare results from the URANS and the LES with the available measurement to understand the underlying flow physics of fan wake development/decay in a modern fan stage.

Table 1
R4 Rotor Design Parameters

No. of blades	22
Fan diameter	22 in. (55.9 cm)
Corrected tip speed	1,215. ft/s (370.3 m/s)
Corrected RPM (RPMC)	12,656
Corrected fan weight flow	100.5 lbm/s (45.59 kg/s)
Stage pressure ratio	1.47
Bypass ratio	8.85
Fan radius ratio	0.30



Figure 1 Test fan stage model

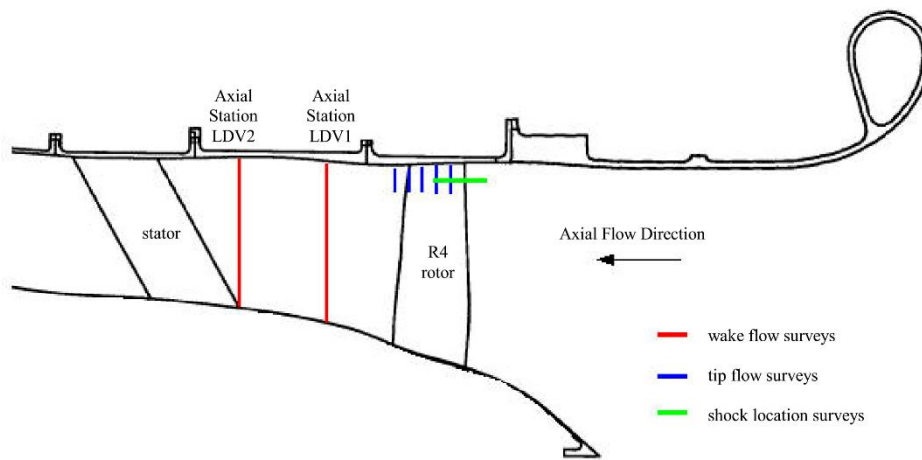


Figure 2 Schematic side view and LDV survey locations

2.0 TEST FAN STAGE (NASA R4) AND THE LASER VELOCIMETER MEASUREMENT

Figure 1 shows the test model installed in the NASA Glenn 9 X 15 Foot Wind Tunnel. The schematic side view of the fan stage and LDV survey locations are shown in Figure 2. The R4 Rotor design parameters are given in Table 1. The flow field measurements were conducted with 22 rotor blades, designated as R4 design by the manufacturer (General Electric), and 26 outlet guide vanes. As shown in Figure 2, the outlet guide vanes were swept back 30 degrees for the acoustic purpose.

The LDV wake surveys were performed at two LDV survey locations, shown in Figure 2, at 50%, 61.7%, 87.5%, and 100% design rotor speed. The fan tip flow survey was conducted at 5 axial locations (25%, 50%, 75%, 100%, and 125% of the static rotor blade tip chord) and three different fan speeds (61.7%, 87.5%, and 100% fan design speed). The measured data were processed in a way to assess acoustic behavior of the flow field. Details of the measurement system and all of the data reduction procedures are given by Podboy et al. [7]. Further tests for the fan noise source diagnostic were reported by Hughes et al. [8] and Podboy et al. [9].

2.1 LES and Computational Grid

The Development of the fan wake and its interaction with the following blade row has been studied extensively. Extensive experimental and theoretical studies have been reported over the last half century. The wake of the fan rotor blade is highly three-

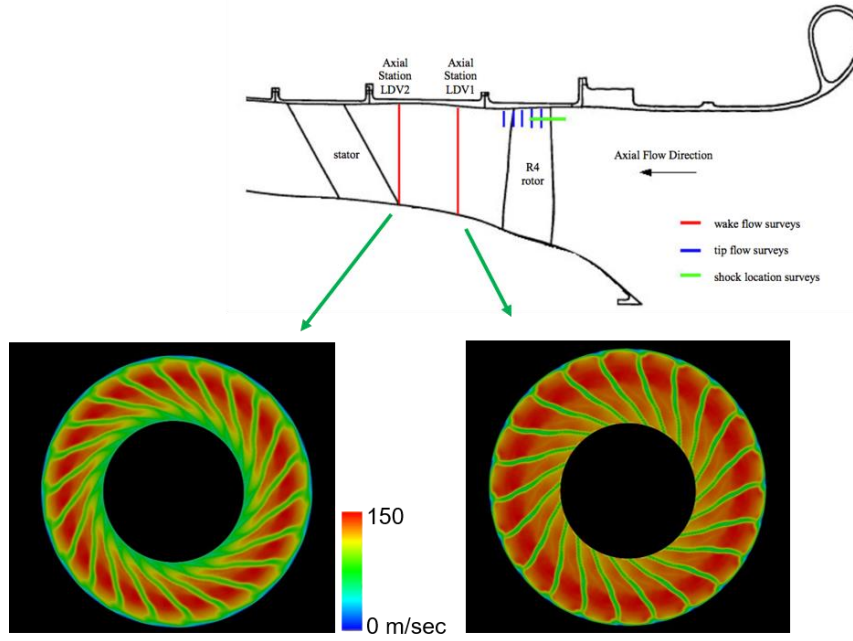


Figure 3 Average passage mean velocity at survey stations

dimensional and the decay characteristics of fan rotors are quite different, even with the similar operating conditions. It's generally believed that RANS and URANS do not calculate the development and decay of the fan wake consistently. The calculated decay rate of the fan wake depends heavily on the applied turbulence model with the RANS/URANS approach. Higher fidelity simulation tools, like LES and DNS, could provide a more consistent wake decay in addition to the turbulence properties. In the current study, both URANS and LES are applied to study the development of the fan wake. The simulated flow fields are compared with each other and the available LDV measurement. A standard two-equation turbulence closure model was used for the current URANS simulation.

With spatially-filtered Navier-Stokes equations, the subgrid-scale stress tensor term needs to be modeled properly for the closure of the governing equations. A Smagorinsky-type eddy-viscosity model was used for the subgrid stress tensor, and the standard dynamic model by Germano et al. [10] was applied.

In the current study, the governing equations are solved with a pressure-based implicit method using a fully conservative control volume approach. A third-order accurate interpolation scheme is used for the discretization of convection terms and central differencing is used for the diffusion terms. For the time-dependent terms, an implicit second-order scheme is used and a number of sub-iterations are performed at each time step. Approximately 8000 time steps are used for one rotor revolution.

Standard boundary conditions for the multi-blade rows were applied at the boundaries of the computational domain [6, 11]. The inflow boundary of the computational domain was located 20 average blade heights upstream of the rotor leading edge in order to dampen out any possible reflections. Likewise, the outflow boundary was located 20 blade heights downstream from the trailing edge. Circumferentially averaged static pressure at the exit boundary casing was specified to control the mass flow rate. Non-reflecting boundary conditions were applied at the inlet and exit boundaries.

The current fan stage has 22 fan blades and 26 OGV blades. As the main focus of the present simulation is to study the development of the fan wake, the number of OGV blades was changed to 22. Several simulation grids were examined to see how well the wake decay process is calculated, ranging from about 100, 140, and 160 million total grid points for the one to one blade count. Wake development was fairly well calculated with both the 140 and 160 million node grids. The final computational grid was 386 nodes in

the blade-to-blade direction, 384 nodes in the spanwise direction, 720 nodes for the rotor, and 380 nodes for the OGV in the streamwise direction. The fan rotor tip clearance geometry is represented by 60 nodes inside the tip gap in an attempt to accurately resolve the tip clearance flow field. I-grid topology is used to reduce grid skewness and a single-block grid is used. The wall resolution is within the range $Dx^+ < 15$, $Dy^+ < 5.0$, and $Dz^+ < 15$ in the streamwise, pitchwise, and spanwise directions.

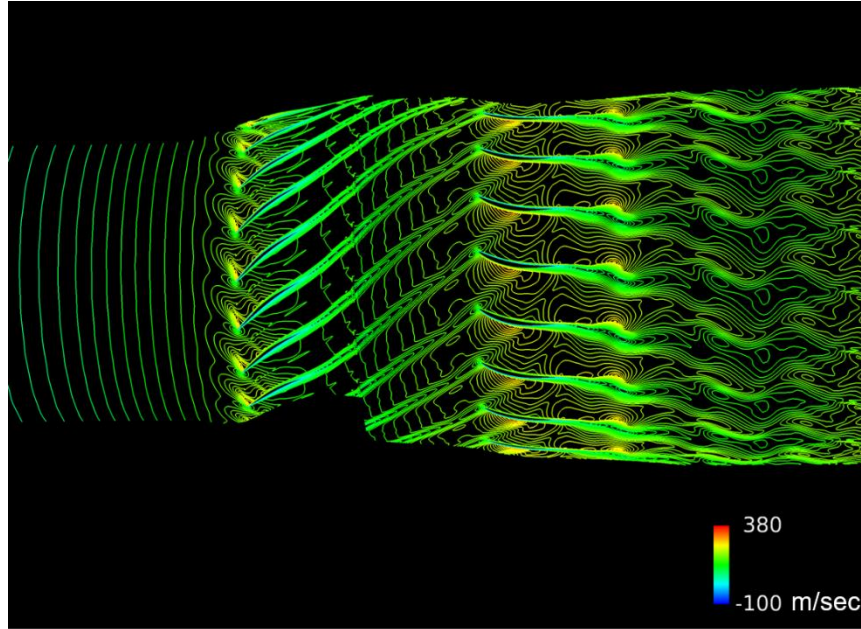


Figure 4 Instantaneous axial velocity distribution at mid-span from URANS, 100% rotor speed

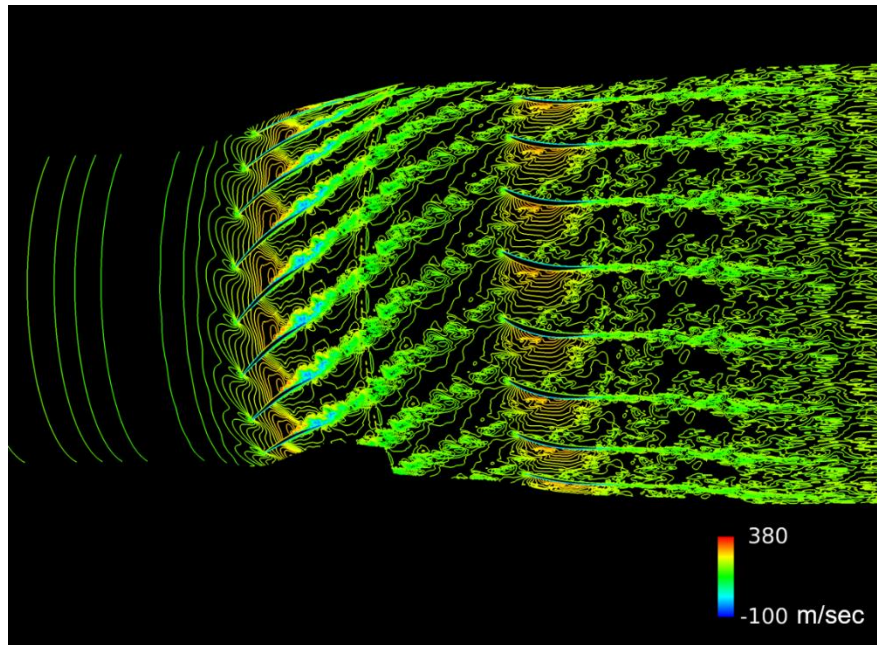


Figure 5 Instantaneous axial velocity distribution at mid-span from LES, 100% rotor speed.

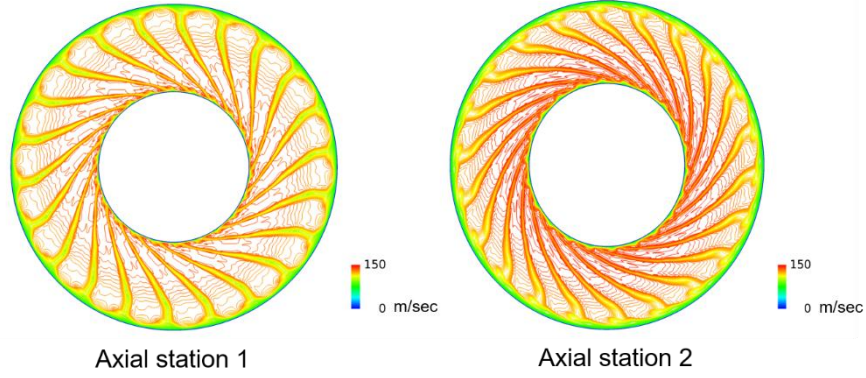


Figure 6 Instantaneous distribution of axial velocity at mid-span from URANS, 61.7% rotor speed

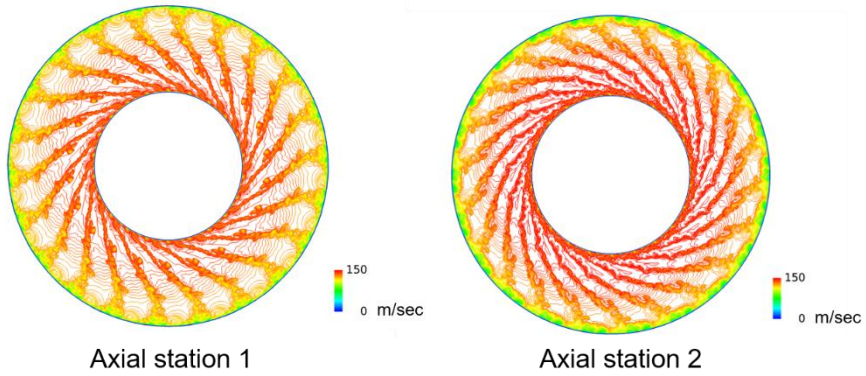


Figure 7 Instantaneous distribution of axial velocity at mid-span from LES, 61.7% rotor speed

All the computations were performed with NASA's Pleiades supercomputing system, which allows parallel computation with multiple processors.

2.2 Overall Flow Field

Figure 3 shows average passage mean velocities measured at two LDV measurement stations at 100% rotor speed. The measured mean velocities in the Figure 3 are average passage results, with the averaged passage data duplicated for full annulus.

The data shown in Figure 3 show flow non-uniformities, which contribute to the rotor-stator interaction noise produced by the stage. Two main contributors to this noise are the viscous fan wake and the fan tip vortices. Discrete tones are generated by the periodic variations in the mean flow and the broadband noise is generated by the random fluctuations in the flow. The noise is generated when the wake flow non-uniformities are convected downstream and interact with the stator vanes. Therefore, accurate prediction of the wake development is necessary to estimate fan noise generation. The measured wake profiles in Figure 3 show the rate of wake decay from measurement station 1 to station 2. Instantaneous axial velocity distribution at mid-span from the URANS and LES are compared in Figures 4 and 5. As the spacing between the fan and the OGV is relatively large, the calculated flow field from URANS is almost steady while the flow field from LES shows flow fluctuations due to the movements of calculated small vortices in the fan wake. It's obvious from the instantaneous flow fields in Figures 4 and 5 that fan tonal noise can be calculated directly with either URANS or LES with a certain degree of uncertainty. However, LES is necessary to calculate broadband noise from the simulation.

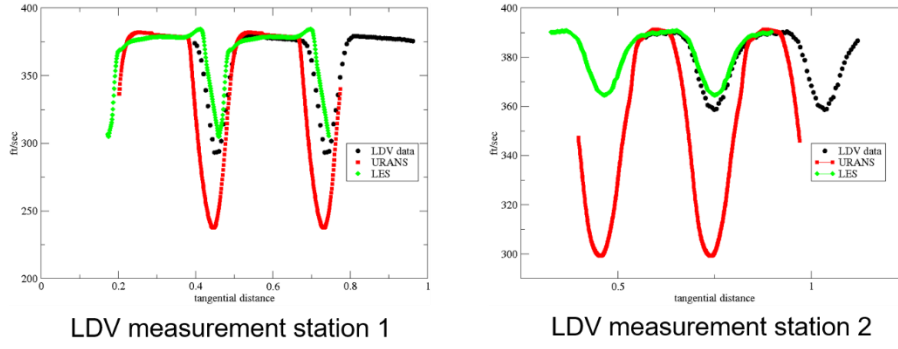


Figure 8 Comparison of time-averaged wake profile at mid-span, 61.7% rotor speed

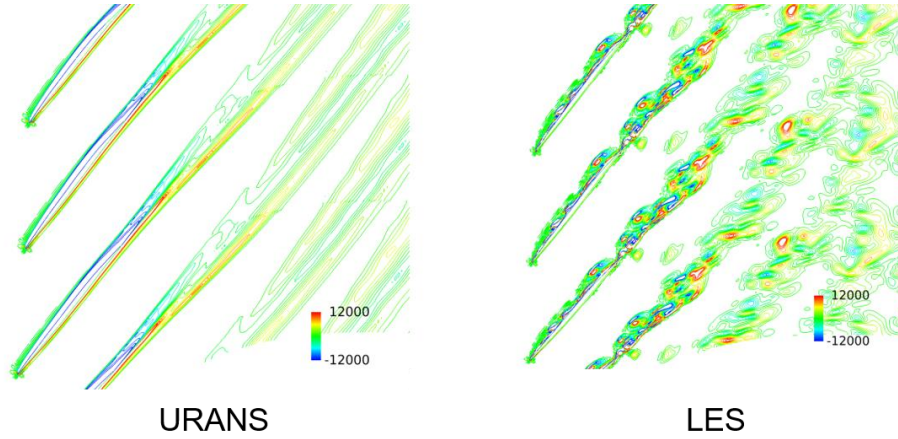


Figure 9 Comparison of vorticity distribution at mid-span, 61.7% rotor speed

3.0 COMPARISON OF LES AND URANS FOR THE WAKE PROFILE

Instantaneous axial velocity distributions at 61.7% rotor speed, which represent the fan operation at approach condition, are shown in Figures 6 and 7. The instantaneous axial velocity distributions at two measurement stations from LES and URANS show the overall development of the fan wake. URANS calculates a deeper wake profile at both measurement stations and the wake decays less than the LES calculates. Figure 8 compares changes in the time-averaged wake profile from LES and URANS at mid-span from measurement station 1 to station 2 with the LDV measurement. At measurement station 1, URANS calculates a deeper wake profile compared to the LES. The time averaged wake profile from the LES matches well with the LDV data. Decay of the fan wake from station 1 to station 2 is calculated quite differently by LES and URANS. URANS indicates that the fan wake decays much less than LES and LDV measurement. To find the flow mechanism causing this difference in the rate of wake decay, flow fields calculated from LES and URANS are further analyzed. Figure 9 compares the instantaneous distribution of the spanwise component of vorticity from URANS and LES. As the turbulence closure of the URANS intended, URANS does not calculate small vortex structures. On the other hand, the LES simulates small eddies in the wake. The actual fan wake is the flow region where small eddies with a varying length scale are concentrated. As the wake is convected downstream, interaction among these eddies changes the wake profile. Naturally LES should simulate the development of such a wake if an adequate computational grid and time steps are used.

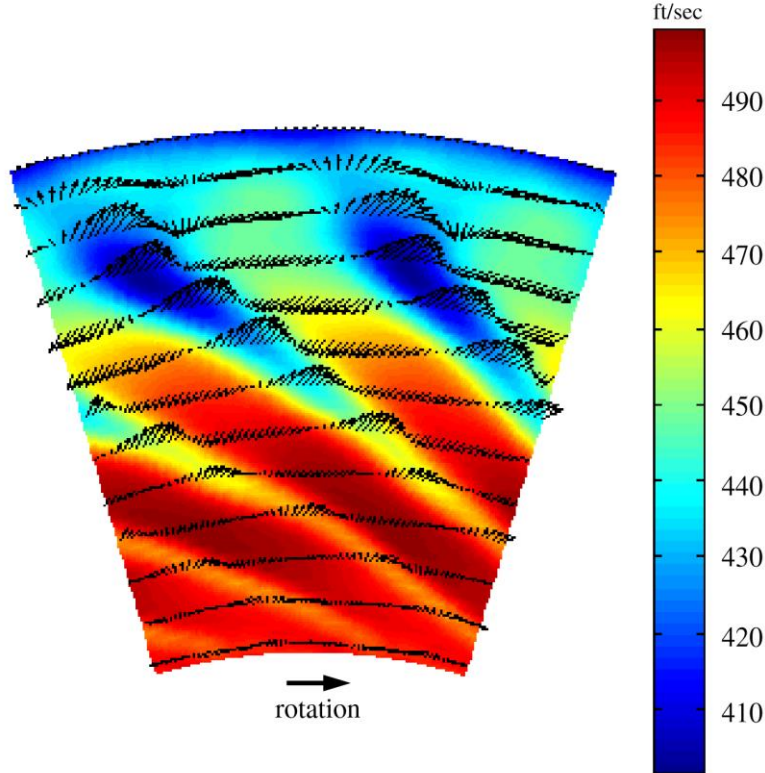


Figure 10 Distribution of measured secondary velocity vectors (upwash and spanwise) with color contours of streamwise velocity at station 2, 61.7% rotor speed

4.0 UNSTEADY CHARACTERISTICS OF THE WAKE

A Hot-wire wake survey was also used to learn more about the flow unsteadiness in the experimental program [9]. As single-point hot-wire measurements were used, the resulting length scale corresponds to the length scale in the streamwise direction. Therefore, local velocity is decomposed into streamwise, spanwise and upwash directions. The upwash and the spanwise velocity components are defined such that their circumferentially-averaged values are zero. The measured velocity distribution at measurement station 2 in this coordinate system at 61.7% speed is shown in Figure 10. In Figure 10, color contours show streamwise velocity. In Figure 10 the actual secondary velocity vectors do not lie in the plane of the figure. For presentation purposes, the secondary vectors are shown as if they lie on this measurement plane. Two cross-stream velocity vectors are plotted on top of the color contours in Figure 10. Figure 10 clearly shows that the fan wake region in the passage and upwash and spanwise velocities in the wake region are larger than the circumferentially averaged value. In this coordinate system, the flow in the wake region tends to flow radially outward while the flow in the clean part of the passage, between the blade wakes, the flow has a tendency to move in the opposite direction. Calculated instantaneous velocity distributions from URANS and LES at the same measurement location are shown in Figures 11 and 12 in the new coordinate system. The wake region from LES occupies about half of the passage, similar to the measurement in Figure 10. URANS calculates a much deeper wake, which occupies a much narrower area than the measured data. Both LES and URANS show similar characteristics of secondary velocity vectors. In order to minimize unsteady lift and to decrease the tonal noise on the downstream stator vanes, the vanes are oriented in such a way that the amplitude of the mean flow oscillations normal to the vane surface is minimized. Velocity distributions in Figures 10, 11, and 12 indicate that the overall orientation of the secondary vectors from LES agrees better with the measured data than that of URANS.

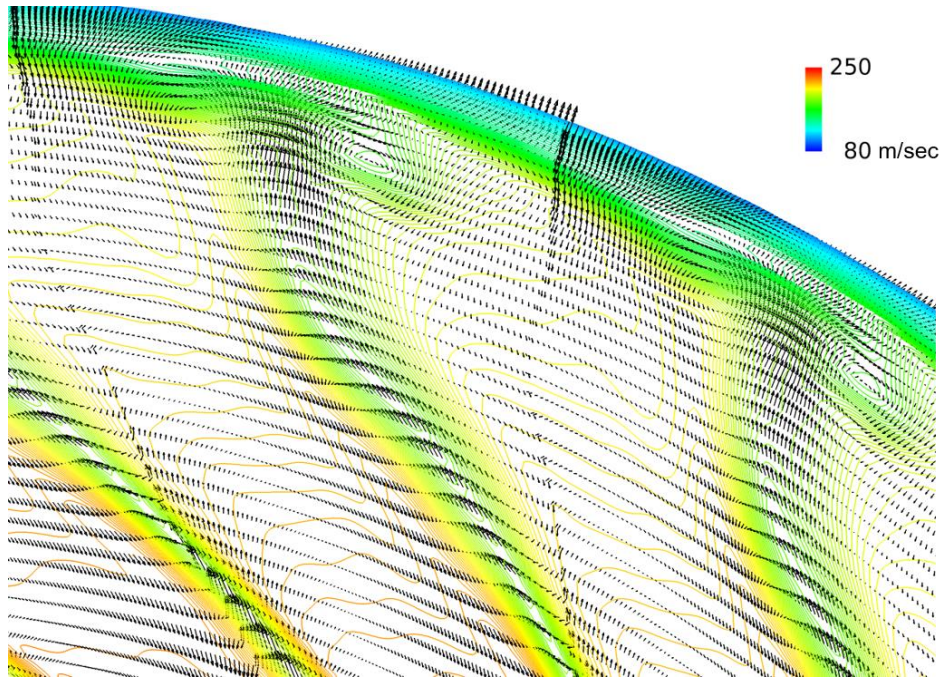


Figure 11 Distribution of secondary velocity vectors (upwash and spanwise) with color contours of streamwise velocity at station 2, 61.7% rotor speed, from URANS

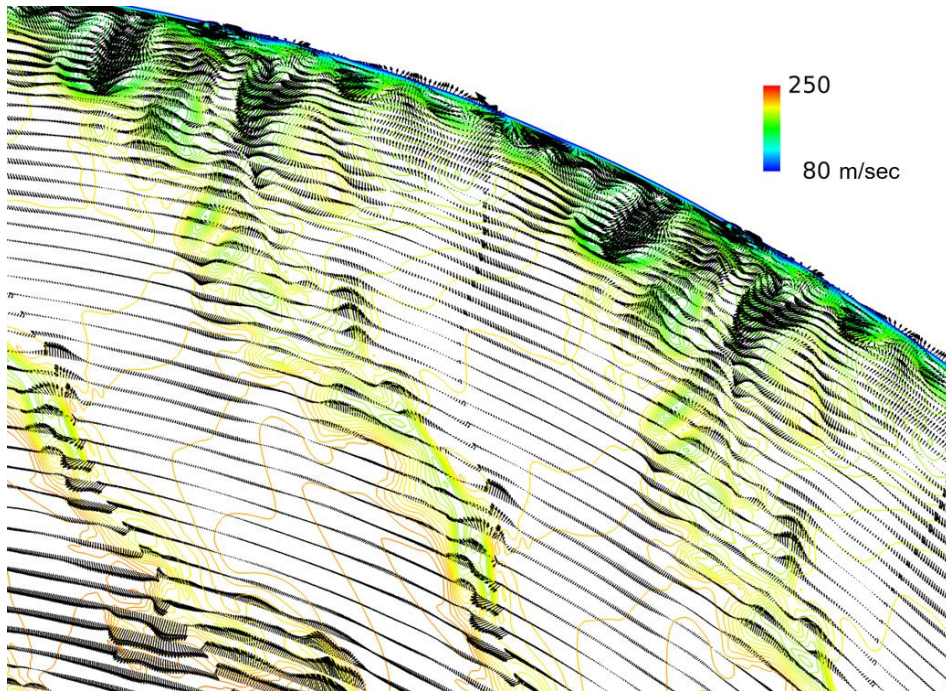


Figure 12 Distribution of secondary velocity vectors (upwash and spanwise) with color contours of streamwise velocity at 61.7% rotor speed, from LES

Power spectra computed from the upwash velocities can be used to get insights into the character of the noise spectrum from the rotor-wake/stator-vane interaction. Figure 13 shows power spectra computed from the measured upwash velocities at two measurement locations at 97% span and 81% span [9]. At 97% span, the probe is located in the tip flow region and the flow in this region is mostly turbulent. The spectra at 97% span shows higher broadband levels than that of the 81% span with less tonal content. Power spectra computed from the LES flow field at the second measurement station is given in Figure 14. The spectra from LES agrees reasonably well with the measured data. The total sampling time for the Power Spectral Densities (PSDs) from LES in Figure 14 is about

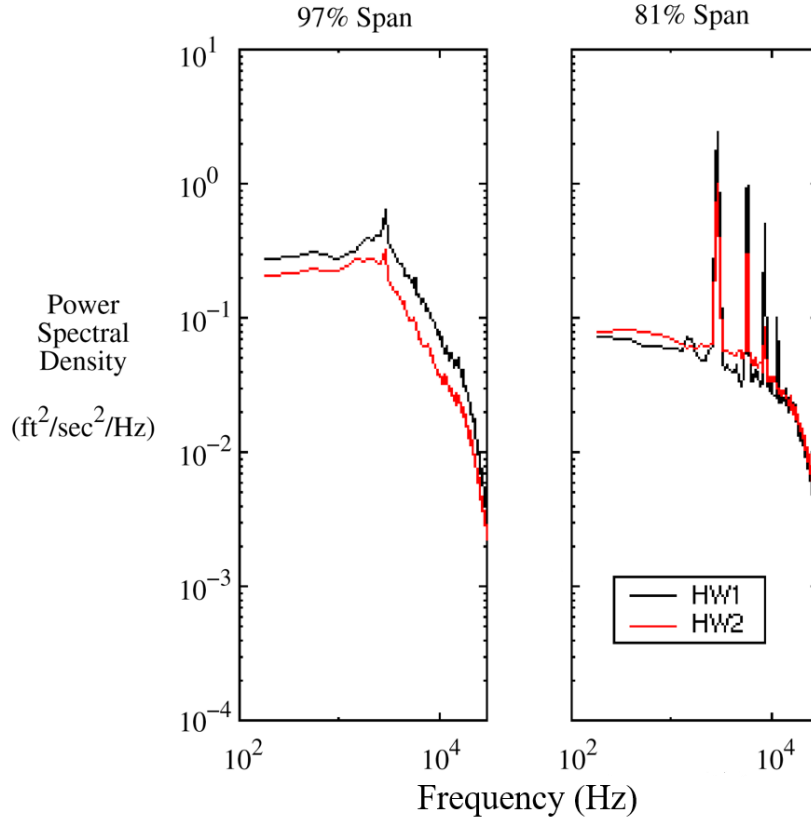


Figure 13 PSD computed from measured upwash velocity at measurement stations, 61.7% rotor speed

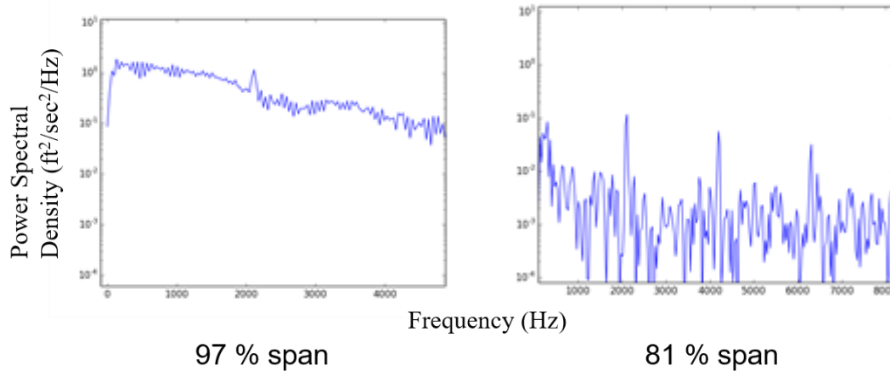


Figure 14 PSDs of upwash velocity from LES at station 2, 61.7% rotor speed

0.03 seconds, while the measured PSD is based on a much longer sampling period. However, the level of peak values and the frequency components of the peaks are calculated reasonably well. The agreement between the measured and the calculated PSDs is expected to improve with longer sampling periods from the ongoing LES simulation. The results shown in Figures 13 and 14 indicate that LES with the currently applied computational grid does simulate unsteady flow characteristics with reasonable accuracy.

5.0 CONCLUDING REMARKS

The development of the fan wake in a transonic fan stage (NASA R4 fan stage) was investigated in detail with the Unsteady Reynolds-averaged Navier-Stokes approach (URANS) and a Large Eddy Simulation (LES). Two main observations from the current study are as follows:

1. Comparisons of time-averaged wake profiles at two measurement planes among LDV data, URANS, and LES show that the current URANS calculates deeper wake profiles. URANS calculates a much slower rate of wake decay than the LDV measurement. The wake profile and decay rate from LES agrees well with the LDV measurement. URANS simulation with a different turbulence closure model could produce different wake profiles. A similar observation was reported in a different study of URANS wake simulation in a compressor stage with different turbulence models.
2. Upwash velocity distributions from the URANS and the LES simulation are quite different in details, although the overall trend is calculated correctly by both approaches. Orientation of the secondary velocity vectors from the upwash and spanwise velocity components from the LES seems to agree better with the LDV measurement.
3. Power spectra of the upwash velocity from the LES of the current setup agrees fairly well with the single-point hot-wire measurement.

Further analyses based on finer computational grids are being conducted for further details of the unsteady flow characteristics. The current LES is being applied to investigate fan intake interactions for supersonic airport noise technology as a part of the NASA Commercial Supersonic Technology (CST) program.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the support of this work by the NASA Commercial Supersonic Technology (CST) program. Edmane Envia, Gary Podboy and Dennis Huff of NASA Glenn provided details of the measurement procedure and experimental data for the investigation. The authors appreciate greatly their guidance for the current study.

REFERENCES

- [1] E ENVIA, "Fan Noise Reduction: An Overview," *39th Aerospace Sciences Meeting and Exhibit*, AIAA Paper 2001-0661, 2001.
- [2] T ZAKI, J G WISSINK, W RODI, P A DURBIN, "Direct Numerical Simulations of Transition in a Compressor Cascade: The Influence of Free-Stream Turbulence," *Journal of Fluid Mechanics*, vol. 665, pp. 57-98, 2010.
- [3] N GOURDAIN, "Validation of Large-Eddy Simulation for the Prediction of Compressible Flow in an Axial Compressor Stage," *ASME Turbo Expo: Power for Land, Sea, and Air*, vol. 6C: Turbomachinery, GT2013-94550, 2013.
- [4] C HAH, J KATZ, "Investigation of Turbulent Tip Leakage Vortex in an Axial Water Jet Pump with Large Eddy Simulation," *ASME Fluids Engineering Division Summer Meeting*, vol. 1, Symposia Parts A and B, pp. 135-142, FEDSM2012-72121, 2012.
- [5] D PAPADOGIANNIS, F DUCHAINE, F SICOT, L GICQUEL, G WANG, "Large Eddy Simulation of a High Pressure Turbine Stage: Effectws of Sub-Grid Scale Modeling and Mesh Resolution," *ASME Turbo Expo 2014: Turbine Technical Conference and Exposition*, vol. 2B: Turbomachinery, GT2014-25876, 2014.
- [6] C HAH, "Effects of Double-Leakage Tip Clearance Flow on the Performance of a Compressor Stage with a Large Rotor Tip Gap," *ASME Journal of Turbomachinery*, vol. 139, no. 6, TURBO-16-1291, 2017.
- [7] G PODBOY M KRUPAR, C HUGHES, R WOODWARD, "Fan Noise Source Diagnostic Test – LDV Measured Flow Field Results," *8th AIAA/CEAS Aeroacoustics Conference and Exhibit*, AIAA Paper 2002-2431, 2002.

- [8] C E HUGHES, R J JERACKI, R P WOODWARD, C J MILLER, "Fan Noise Source Diagnostic Test – Rotor Alone Aerodynamic Performance Results," *8th AIAA/CEAS Aeroacoustics Conference & Exhibit*, AIAA Paper 2002-2426, 2002.
- [9] G PODBOY, M KRUPAR, S HELLAND, C HUGHES, "Steady and Unsteady Flow Field Measurements within a NASA 22 Inch Fan Model," *Aerospace Sciences Meetings*,, 40th AIAA Aerospace Sciences Meeting and Exhibit, AIAA Paper 2002-1033, 2002.
- [10] M GERMANO, U PIOMELLI, P MOIN, W H CABOT, "A Dynamic Subgrid-Scale Eddy Viscosity Model," *Physics of Fluids A* 3(7), 1991.
- [11] C HAH, H SHIN, "Study of Near-Stall Flow Behavior in a Modern Transonic Fan with Compound Sweep," *ASME Journal of Fluids Engineering*, vol. 134, no. 7, 2012.